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Observational Constraint on the Antiproton Lifetime from Nucleon Decay in Clusters of Galaxies

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Abstract

The diffuse γ-ray background is used to constrain antiproton lifetime limits in a universe which contains large domains of antimatter. A limit on the antiproton lifetime over branching ratio, $\tau_{\overline{p}}/Br$ is obtained in terms of, f_{gl} , where f_{gl} is the global antimatter:matter ratio. We use baryons in clusters of galaxies as a laboratory for the study of nucleon decay. For the antiproton decay mode, $\overline{p} \longrightarrow e^- + \pi^\circ$, we are able calculate an expected absolute γ-ray flux as a function of $\tau_{\overline{p}}/Br$ and the parameter f_{gl}. Comparison of the predicted flux with the measured diffuse γ-ray background gives limits on $\tau_{\overline{p}}/Br$. For a baryon symmetric universe, $f_{gl} = 1.0$, we obtain an improvement in the antiproton lifetime limit of 11 orders of magnitude over current cosmic ray limits, and 18 orders of magnitude over current laboratory limits.

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1 Introduction

We begin with two observations:

1.) Due to CPT invariance, the antiproton is expected to have an identical lifetime with that of the proton. However, the current experimental situation is such that there exists some 33 orders of magnitude difference between branching ratio dependent lifetime limits for the proton vs. the antiproton (Becker-Szendy et al., 1990, Golden et al. 1979, for review see Aguilar-Benitez 1992). Indeed there is but one published test of CPT for baryons, and this involves proton and antiproton inertial mass differences (Gabrielse, 1990). The technical difficulties of producing and containing macroscopic quantities of antiprotons for long time scale laboratory observations make it unlikely that lifetime limits for the antiproton will rival, in the near future, those obtained for the proton.

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2.) We note that our local universe, the galaxy, is observed to be baryon asymmetric with matter dominating. The local antimatter:matter ratio is known to be, $f_{local} \leq 10^{-10}$ Excellent reviews on this subject have been done, see Steigman (1974, 1976), and more recently, Ormes and Streitmatter (1992), Dolgov (1993). Arguments for baryon symmetric (Stecker 1971, 1982, 1985; Brown & Stecker 1979; Senjanovic & Stecker 1980; Sato 1981), as well as baryon asymmetric universes have been made (eg. Turner and Kolb 1990). However, as emphasized by Ormes and Streitmatter, *there are currently no experimental limits on the global antimatter:matter ratio* (ie. greater than the local cluster scale, $\sim 10\,Mpc$)

$$0 \leq f_{gl}^{experiment} \leq 1. \tag{1.1}$$

Therefore, with the domain scale suggested by the local cluster, we consider a universe in which unmixed domains of matter and antimatter exist on scales of cluster size and greater. We then ask what may be observed if the antiproton should have a lifetime different from that of the proton. For antimatter clusters with antiprotons decaying via, $\overline{p} \longrightarrow e^- \pi^\circ \longrightarrow 2\gamma$, we expect a contribution to the diffuse γ-ray background. A single rich cluster of $10^{15}\,M_\odot$ represents $\sim 10^{70}$ nucleons, and there are $\sim 10^4$ clusters with mass greater than $10^{13} M_\odot$. Because the number density and mass content of clusters is well determined observationally by X-ray and optical studies, we are able to calculate an expected diffuse γ-ray background due to $\overline{p}$ decay in antimatter clusters. The expected flux due to $\overline{p}$ decay is given in terms of the antiproton lifetime over branching ratio, $\tau_{\overline{p}}/Br$, and the global antimatter:matter ratio, f_{gl}. This flux is compared to the measured diffuse γ-ray flux to give improved antiproton lifetime limits.

2 Flux Calculation

For a matter dominated universe with zero cosmological constant, the diffuse flux per unit energy interval $dE_\circ$, as measured by an observer at the present epoch, due to discrete sources at redshift z, is given by the general expression,

$$\frac{d\Phi}{dE_\circ} = \frac{c}{4\pi\, H_\circ} \int \frac{\Gamma(E_\circ(1+z), z)}{(1+z)^4(1+\Omega z)^{\frac{1}{2}}} dz, \tag{2.1}$$

where $H_\circ$ is the current Hubble parameter, taken to be 75 $(km/s/Mpc)$, and Ω is the cosmic density parameter taken to be 1. The effects of cosmological expansion, namely photon redshift, the decreased rate at which photons are recieved, and the shift in the unit energy interval, are taken into account (Weinberg 1972).

In the cluster frame, the emission rate of photons per volume per unit time per unit energy interval dE is given by,

$$\Gamma(E) = R\, \rho\, \frac{dN_\gamma}{dE}, \tag{2.2}$$

where R is the decay rate of antiprotons per cluster, ρ is the number density of clusters, and $\frac{dN_\gamma}{dE}$ is the differential photon spectrum per $\overline{p}$ decay.

The decay rate per antimatter cluster is given by,

$$R = \frac{N_b \times Br}{\tau_{\bar{p}}}, \tag{2.3}$$

where N_b is the number of baryons in the cluster. This can be written,

$$R = \frac{\Omega_b \, m \, N_{15} \, Br}{\tau_{\bar{p}}}, \tag{2.4}$$

where Ω_b is the cluster baryonic fraction, m is $\frac{M_{tot}}{10^{15} M_\odot}$, the total cluster mass (dark+ baryonic matter) normalized to $10^{15}\, M_\odot$, and $N_{15} = 1.2 \times 10^{72}$ ($nucleons/10^{15}\, M_\odot$).

The baryonic mass content in clusters is found to reside in two principal components, a hot diffuse gaseous halo ($r \sim 1\, Mpc$) and the galaxies themselves (Gioia et al., 1990; Edge et al., 1990; Jones & Forman 1992). The diffuse gas is studied primarily through observation of X-ray emission. The halo is well modeled as an isothermal spherical distribution with temperature typically $10^7 - 10^8\, K$. Knowledge of the temperature allows the radial X-ray surface brightness distribution to be inverted to give the radial gas density, hence the mass (Cavaliere and Fusco-Femiano 1976). Clusters are to first approximation dynamically relaxed. Thus, application of the virial theorem to observations of peculiar velocities of individual galaxies allows determination of the cluster mass.

Observations are consistent with $\Omega_b \geq 0.01$ (see White 1992 for review). It is also found that the dominant baryonic component resides in the gaseous halo, not the galaxies, with $m_{gas} = 2 \sim 10\, m_{stars}$. Thus, up to a factor of 2, we can safely ignore galactic baryons and focus on gaseous baryons. This avoids modelling γ-ray attenuation effects in individual stars and galaxies. Attenuation of photons in the range from 10 to 500 Mev is due to Compton scattering and Pair production, with a peak absorption cross section of $\sigma_{abs} = 5 \times 10^{-26}\, cm^2$ (Stecker 1971) . For an integalactic electron density of $n = 10^{-5}$ corresponding to a critical universe, $\Omega = 1$ and a distance of 3000 Mpc the absorption is less than 1 %. Absorption in the intracluster medium is also expected to be small, with densities $\sim 10^{-2}$, for a typical cluster core $\sim 2\, Mpc$ we find again the absorption < 1 %.

We adopt the standard Press-Schechter form $d\rho(m,z)/dm$, for the cluster differential number density (Press & Schechter 1974, Perrenod 1980). The cluster differential number density, for clusters with total mass between (m, $m + dm$) in the redshift interval (z, $z + dz$) is,

$$\frac{d\rho(m,z)}{dm} = \rho_\circ (1+z)^4 \frac{m}{m^\star_\circ}^{-(1+\alpha)} exp[-(1+z)^2 \frac{m}{m^\star_\circ}^{2(1-\alpha)}] \tag{2.5}$$

where $m^\star_\circ$ is the characteristic mass of the distribution at $z = 0$. The characteristic mass as a function of epoch is given by,

$$m^\star(z) = m^\star_\circ (1+z)^{1/(\alpha-1)}. \tag{2.6}$$

Here, α, is related to the spectral index, β, of primordial density fluctuations expressed as a power spectrum, $P(k) \sim k^\beta$, with $\alpha = (\beta+3)/6$ (Gott & Turner 1977).

Integrating $\frac{d\rho}{dm}$ over the appropriate redshift interval, $0.01 \leq z \leq 1.0$ and mass range, $10^{13} - 10^{15}\ M_\odot$ we derive an integral density function $\rho(> m)$. For the parameters, $\rho_\circ = 30$, $\alpha = 0.45$, $m_\circ = .18$ we find good agreement between our distribution and an integral mass distribution recently derived from a compilation of optical and X-ray data, given by Bahcall & Cen (1993), see fig. 1. This allows us to express the differential emissivity due to $\overline{p}$-decay as,

$$d\Gamma(E,m,z) = R(m)\,\frac{dN_\gamma}{dE}\,\frac{d\rho(m,z)}{dm}\,dm. \tag{2.7}$$

Nucleons in the cluster halo are nonrelativistic, $\frac{kT}{m_p c^2} \sim 10^{-5}$, and the π° produced in $\overline{p}$-decay has unique momentum, with $\gamma_\pi = 3.56$. The photon spectrum in the comoving frame of the cluster is flat and normalized to 2 photons per decay,

$$\frac{dN_\gamma}{dE} = 4.32 \times 10^{-3}\,(photons MeV^{-1})\ ,\ 9.6 \leq E_\gamma(MeV) \leq 472.5 \tag{2.8}$$

$$\frac{dN_\gamma}{dE} = 0,\ otherwise. \tag{2.9}$$

Taking into account the unknown global antimatter:matter fraction,

$$f = \frac{f_{gl}}{1 + f_{gl}}, \tag{2.10}$$

we calculate the differential γ-ray spectrum $(photons\, cm^{-2}\, s^{-1}\, sr^{-1}\, Mev^{-1})$ with $\Omega_b = 0.01$ and $\frac{f\,Br}{\tau_{\overline{p}}} = 0.5\ (s^{-1})$, $f_{gl} = 1$, fig. 2.

$$\frac{d\Phi^{calc}}{dE_\circ} = \frac{f\,Br}{\tau_{\overline{p}}}\,\frac{\Omega_b\,N_{15}\,c}{4\pi\,H_\circ}\int_{z=0.01}^{1.0}\int_{m=0.01}^{1}\frac{d\Gamma(E_\circ(1+z),m,z)/dm}{(1+z)^4(1+\Omega z)^{\frac{1}{2}}}\,dz\,dm. \tag{2.11}$$

3 Limits

We express the calculated differential spectrum as,

$$\frac{d\Phi^{calc}}{dE_\circ} = \frac{f\,Br}{\tau_{\overline{p}}}\,\frac{d\chi(E_\circ)}{dE_\circ}. \tag{3.1}$$

We use data from the γ-ray sky survey of the SAS-2 satellite which characterized the diffuse γ-ray background in the energy range from 35 to 150 (Mev) (Fichtel et al. 1978; see also Fichtel & Trombka 1981). The best fit *observed* differential diffuse γ-ray spectrum, in the energy range from 35 to 150 (Mev) is given by a power law in energy of the form,

$$\frac{d\Phi^{obs}}{dE} = A_\circ\,{\frac{E}{1\,(Mev)}}^{-\alpha}\ (ph\,cm^{-2}\,s^{-1}\,sr^{-1}\,Mev^{-1}). \tag{3.2}$$

The differential spectral index, α has the value,

$$\alpha = 2.7^{+0.4}_{-0.3}, \tag{3.3}$$

and the normalization constant A_o is determined such that the integral flux above 35 (Mev) has the value $5.7 \pm 1.3 \times 10^{-5}$ $(ph\, cm^{-2}\, s^{-1}\, sr^{-1})$. By requiring that the calculated flux be less than the observed flux we have,

$$\frac{d\Phi^{calc}}{dE} = \frac{f\, Br}{\tau_{\overline{p}}} \frac{d\chi(E)}{dE} < \frac{d\Phi^{obs}}{dE}. \tag{3.4}$$

Rearranging and forming the ratio,

$$\frac{\tau_{\overline{p}}}{Br} > \frac{f\, \frac{d\chi(E)}{dE}}{\frac{d\Phi^{obs}(E)}{dE}}, \tag{3.5}$$

we find the antiproton lifetime limit as a function of energy in figure 3. For the central value of the spectral index, the limit peaks near 300 Mev with a value of $\frac{\tau_{\overline{p}}}{Br} = 10^{26}\,(sec)$ for a symmetric, $f_{gl} = 1$, universe. This limit may be subject to uncertainties due to the calculated spectrum rolling off and is outside the SAS-2 energy region. Restricting ourselves to the energy interval for the SAS-2 data, we find the maximum limit at 150 (Mev), with a value of $5.0^{+2.2}_{-1.1} \times 10^{25.17+0.14,-0.13}\,(sec)$, where the error is the systematic error due to the uncertainty in the differential spectral index. We estimate an additional uncertainty in the cluster density function and baryon fraction of 50 % and 100 % respectively. Combined we estimate an overall uncertainty,

$$\frac{\tau_{\overline{p}}}{Br} = 10^{25.0\pm1.0}\,(sec) \tag{3.6}$$

The antiproton lifetime limit is plotted in fig. 4. as a function of f_{gl}. The present day number of observed X-ray clusters is of order 100. Therefore with the assumption that antimatter exist in discrete units of cluster size, the limit cuts off at an $f_{gl} \sim f = 10^{-2}$. The upper limit to the number of X-ray clusters which will be seen by ROSAT is estimated to be $\sim 10^4$ (Evrard & Henry 1991, Bohringer, H. et al. 1992). This will extend the limit to $f_{gl} \sim 10^{-4}$.

Also shown in figure 4 are current lifetime limits for both the proton and antiproton. Current limits on the proton lifetime for branching ratio independent and branching ratio dependent modes are $5 \times 10^{32}(sec)$ and $3 \times 10^{40}(sec)$ respectively[2] (Aguilar-Benitez, M., et al., 1991). For antiprotons accumulated in a storage ring, $\tau_{\overline{p}} \geq 2.5 \times 10^5(sec)$ (Bregman et. al. 1978; Bell et. al. 1979), and for antiprotons stored in a Penning trap, $\tau_{\overline{p}} \geq 8.8 \times 10^6(sec)$ (Gabrielse et. al., 1990). A more model dependent limit, based on the mean residence time for GeV cosmic ray particles in the galaxy is given by, $\tau_{\overline{p}} \geq 10^{14}(sec)$ (Golden et. a al. 1979; for review see Cesarsky C. J., 1980). The recently approved Fermilab experiment E-868 (Geer et al. 1992) hopes to improve the laboratory antiproton lifetime limit to $O(10^{15})$ seconds.

Limits on the well-mixed fraction of matter and antimatter, f_{mix}, have been derived from a combination of X-ray and γ-ray data. These limits are summarized in Steigman (1976). The vertical dashed lines in figure 4 show the limits to f_{mix} obtained for the galaxy, the Virgo cluster, and the Perseus cluster. It is noted that well-mixed antimatter and matter are ruled out on the cluster scale.

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[2] *Note, for ease of comparison, all time units in this paper are in* ***seconds***.

Several experimental approaches which hope to measure, or at least produce better upper limits on, f_{gl} are underway. A large scale survey using EGRET on the Compton Gamma Ray Observatory (GRO) will be used to search for the γ-ray flux produced by $p\overline{p}$ annihilations from overlapping boundary regions between large scale matter and antimatter domains (Stecker 1971; Fichtel & Trombka 1981; Cline et al. 1990; Gao et al. 1990a; Gao et al. 1990b).

A new class of UV air Čerenkov telescopes, one recently commisioned by the Artemis-Whipple collaboration (Urban et al. 1990;), and one soon to come on line by the CLUE collaboration (Bedeschi et al. 1990), will attempt to measure the $\overline{p}/p$ ratio by the shadowing caused by the geomagnetic field and moon as a charge spectrometer/absorber system. At 1 Tev the separation of the proton/antiproton shadows is 60 mrad. These experiments hope to achieve a threshold of $\sim 1\,Tev$. This technique has recently found the proton shadow at higher energies $\sim$ 10 Tev using either the sun or the moon as absorber material. (Alexandreas et. al. 1991, Amenomori et al. 1993, Fick et al. 1991, Karle et al. 1992.) The Wizard spectrometer will also measure this ratio up to 0.5 Tev (Golden et al. 1990). At TeV energies models for galactic production of antimatter through spallation processes vs models for an extragalactic antimatter component become well separated (Stecker 1985). Therefore, the above mentioned experiments should begin to constrain the $\overline{p}/p$ ratio on global scales.

The most direct observation of antimatter would be the detection of an antinucleon heavier than hydrogen in the cosmic rays. Because of the vanishingly small spallation production cross section for the production of $\overline{He}$, even a single detection of such a nucleon would establish at least one finite size region of antimatter (see Steigman 1976 or Ormes & Streitmatter 1990 for discussion). This observation would push the antiproton lifetime limit to the age of the universe $\sim 10^{17}\,(sec)$.

We have used experimental data from the large scale properties of galaxy clusters to form a lifetime limit on the antiproton. We have been conservative in the choice of all parameters used in forming this limit. It is worth noting that the limit may be improved by a factor of 10 should it be found that the mean value of Ω_b for clusters is $\sim$ 0.1.

We have shown that a symmetric Universe, with unmixed domains of antimatter separated on scales of cluster size or greater, is stable for at least 10^8 Universe lifetimes. Symmetric Universe antiproton lifetime limits derived here represent an improvement of 11 orders of magnitude over current cosmic ray limits, and 18 orders of magnitude over present laboratory limits.

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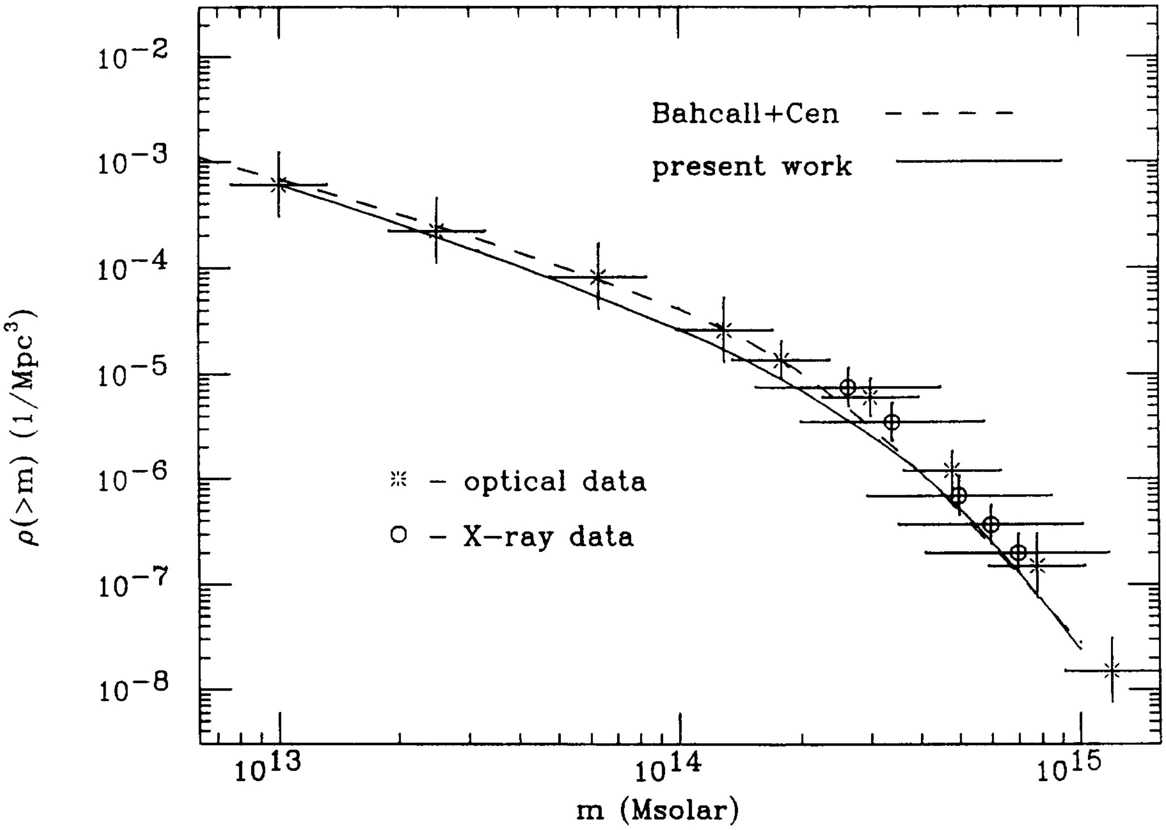

Figure 1: Cluster integral mass function derived from optical and X-ray data taken from Bahcall & Cen (1993), dashed line. Integral mass function derived from Press-Schechter form, solid line. The differential form of this function is used to calculate diffuse γ-ray flux due to $\overline{p}$ decay.

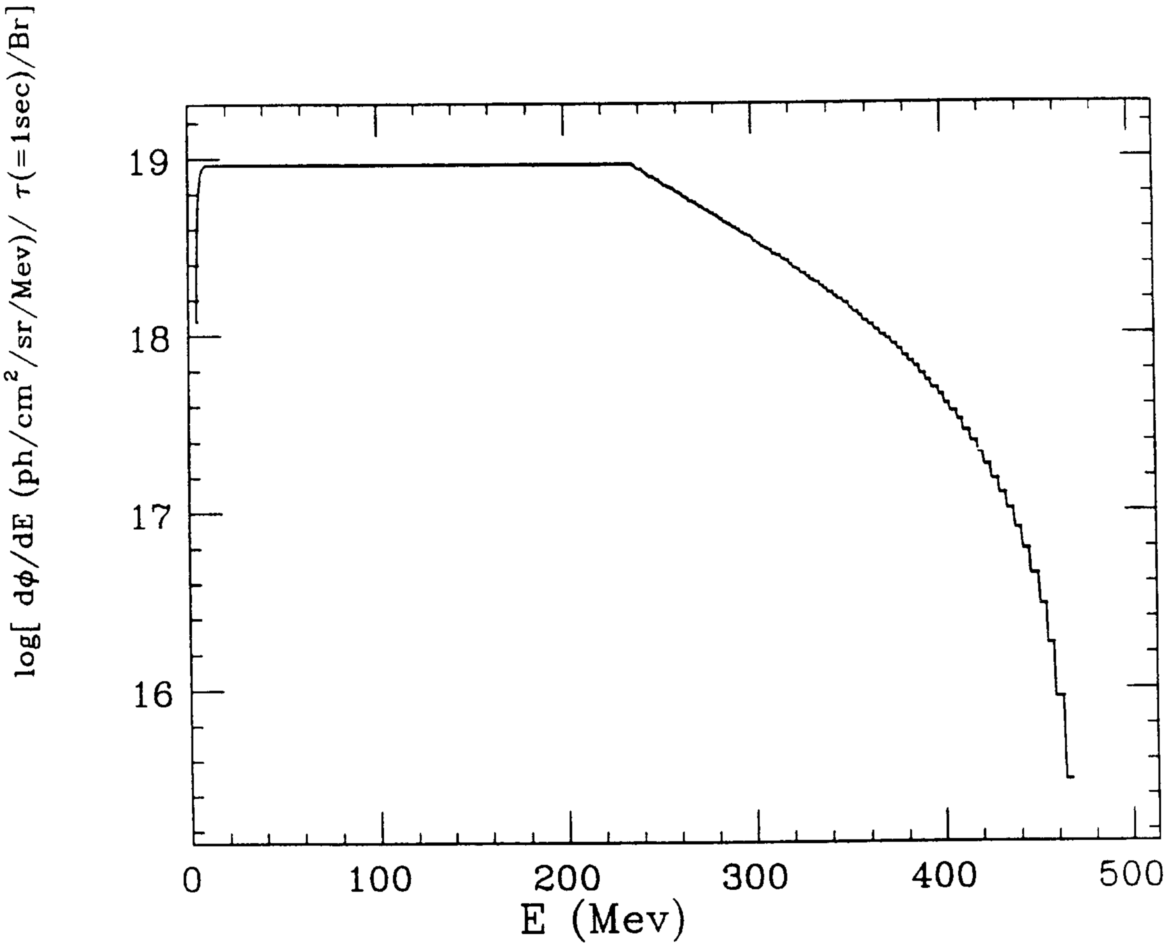

Figure 2: Calculated differential γ-ray spectrum due to $\overline{p}$ decay, $\overline{p} \longrightarrow e^- + \pi^0$ in galaxy clusters. Here f_{gl} is taken to be 1, and $Br/\tau_{\overline{p}}$ is taken to be 1.0 sec^{-1}.

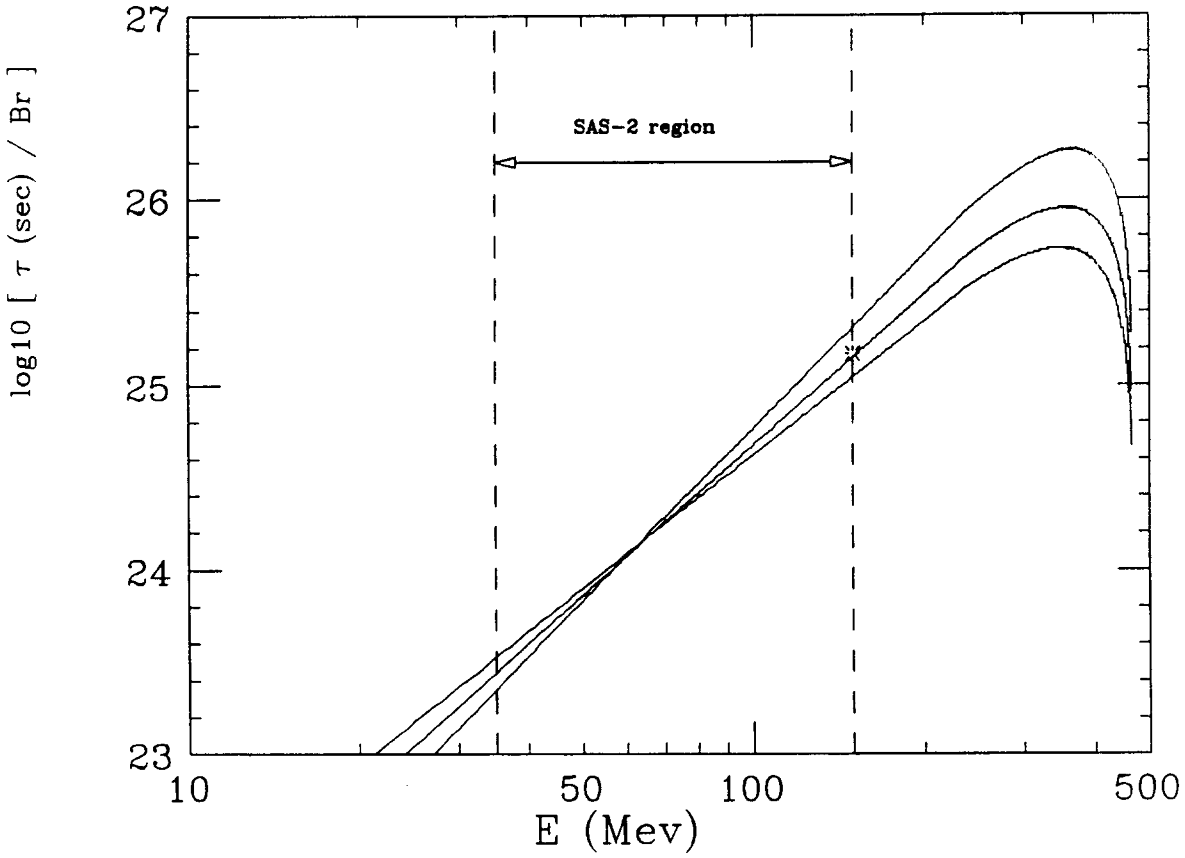

Figure 3: Antiproton lifetime limit determined by comparison of calculated flux to observed differential diffuse γ-ray spectrum (Fichtel et al. 1978). The three curves are due to quoted errors in the differential spectral index, $\alpha = 2.7^{+0.4}_{-0.3}$ For the central value of the best fit differential spectral index of $\alpha = 2.7$ we find a maximum limit, for the SAS-2 energy region, at 150 (Mev), of $\frac{\tau}{Br} = 10^{25.0 \pm 1.0}$ (sec), for a symmetric, $f_{gl} = 1$, universe (indicated by star in plot).

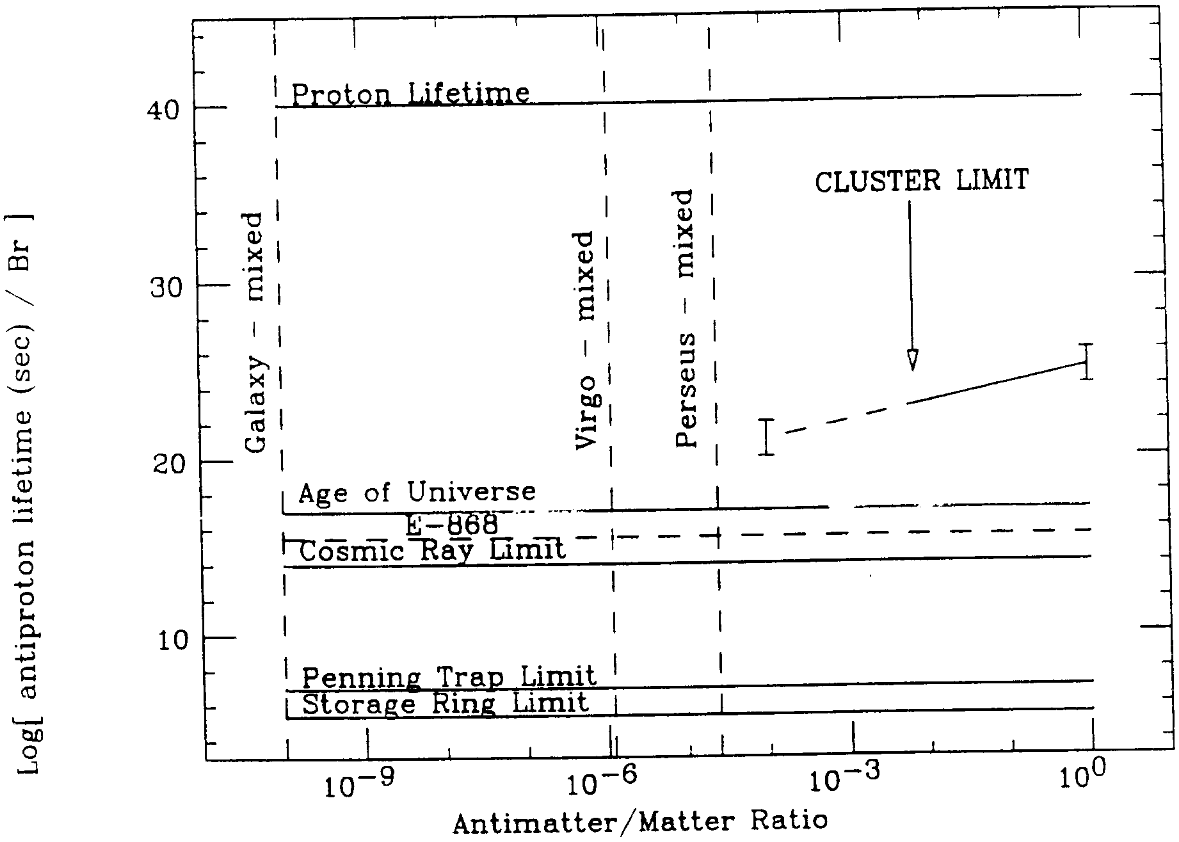

Figure 4: Antiproton lifetime limit from clusters versus the global antimatter:matter ratio, f_{gl}. The limit extends from 10^{-4} , $f_{gl} < 1$, where $f_{gl} = 1$ corresponds to a baryon symmetric universe. Also shown are current antiproton lifetime limits from accelerators (Bell et al., 1979; Bregman et al., 1978;) Penning trap (Gabrielse et al., 1990) and cosmic rays (Golden et al., 1990). For comparison the lifetime limit for the proton is also shown (Becker-Szendy et al., 1990). The vertical lines are limits derived for *well-mixed* matter antimatter regions from X-ray and optical data in the galaxy, Virgo cluster, and the Perseus cluster (Steigman 1976)